



Novel Payload Architectures for LISA

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Overview



- Introduction
- Technical challenges of the LISA mission driving payload architecture
- Pointing/phase crosstalk affecting LISA payload performance and design
- LISA present payload architecture
- LISA alternative payload architecture: Single inertial sensor/ in-field pointing concept
- Conceptual design
- Main technical challenges
- Internal metrology and calibration
- Spherical test mass as an option?
- Summary



Introduction



Why looking into alternative payload architectures, while:

- the present payload configuration has significantly evolved, but not principally changed over the past 10 years
- it is mature (at present study level), comprehensive and consolidated, with some refinement and technology verification still to be done
- no show stoppers have been identified
- it takes advantage of LISA Pathfinder developments on-going and in advanced stage

Justification:

- Cross-check whether the optimum configuration has been found with respect to performance, technical feasibility, budgets, complexity, risk, maturity, AIVT, programmatics and costs
- Explore potential for cost savings, physical budgets reduction (mass, power, envelope), mission simplification
- Potential gateway in response to evolving LISA science requirements (e.g. low frequency band extension)





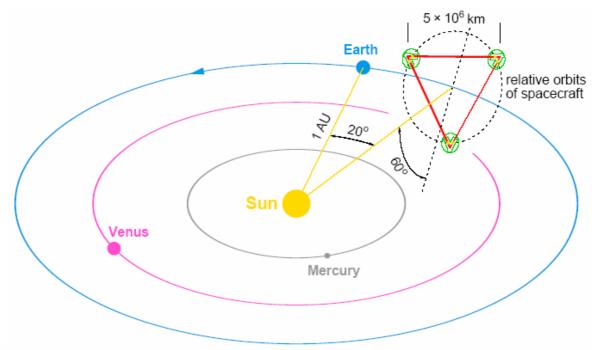
1.Technical challenges of the LISA mission driving payload concepts



The LISA mission



- Mission goal is to detect gravitational waves and characterize sources
- Laser interferometry with three spacecraft flying in a "non-perfect" relative triangular constellation
- Interferometer arm-length: 5 mio km
- Measurement bandwidth: 0.1 mHz 1 Hz





Technical challenges caused by orbit dynamics within the LISA constellation



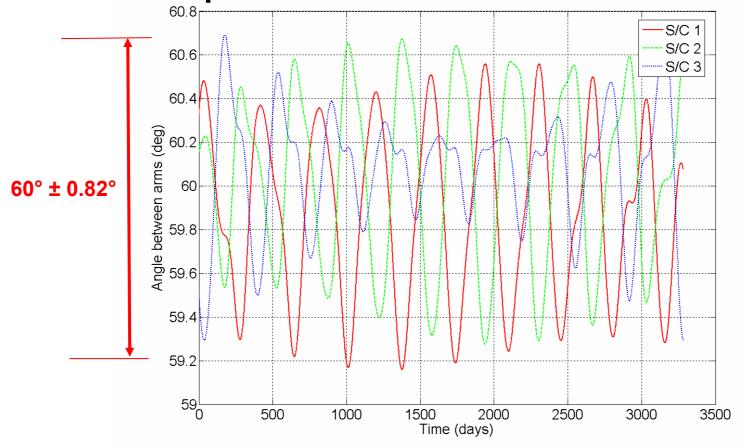
The dynamics of the LISA constellation imposes some peculiar challenges, which are largely driving the payload architecture. The deviation from an ideally, intrinsically stable LISA triangular constellation with equal arms, resting in an inertial frame, leads to following effects:

- Unequal interferometer arm length: laser phase noise dominates phase detection if not compensated for.
- Radial distance variation within the triangular plane: Doppler shift of laser frequency affecting heterodyne detection.
- \Longrightarrow
- Angular variation within the triangular plane: line of sight lateral offset angle "breathing" 60°+- 1°/year.
- In-plane rotation of constellation: fixed offset pointing (nearly) between transmit and received beam.
- Revolution of constellation plane orientation: variable offset pointing between transmit and received beam perpendicular to plane by +- 6 µrad/year.



Annual constellation "breathing" over the mission in plane



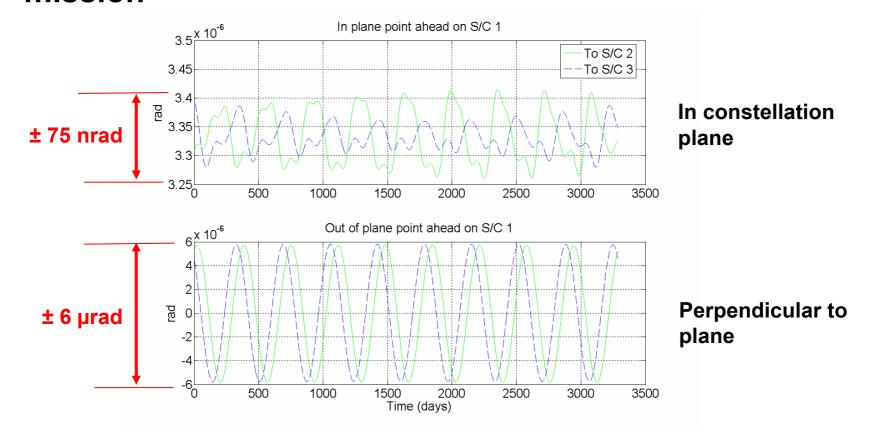


Earth offset (deg)	max Earth range (km)	max excursion (deg)	max range rate (m/s)
21	63499482	1.64	15.77
23	68678518	1.40	15.99
25	73854182	1.25	13.91



Annual offset pointing variation between transmitter and received beam over the mission





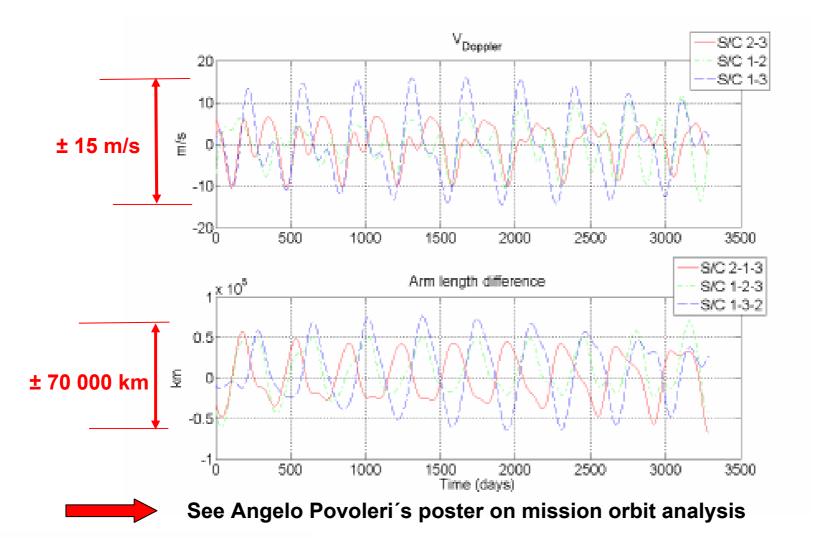
Point ahead angles, as calculated for s/c 1.

The amplitude of the variation is also representative for the other two s/c.



Annual differential range rate and range over the mission







Technical challenges for the LISA laser interferometry



For the LISA laser interferometry proper, the main technical challenges to meet the measurement performance can be grouped into four areas:

- Minimize technically induced laser piston/phase fluctuations
 within the measurement band encountered in the optical system
 between local phase references on the optical bench and the system
 aperture (entrance/exit pupil).
- Provide active guidance and pointing stability for the transmitted and received beam within the measurement band.



- Minimize cross talk effects from pointing jitter to laser beam phase jitter within the measurement band caused by geometric projection effects.
- Minimize straylight and polarisation impact on phase detection performance.

Geometric pointing/phase crosstalk effects (1)



Geometrical projection effects in the near and far field of the laser beams (at local or remote spacecraft, respectively), causing pointing jitter to piston/phase jitter cross talk within the measurement band appear at various places in the measurement chain:

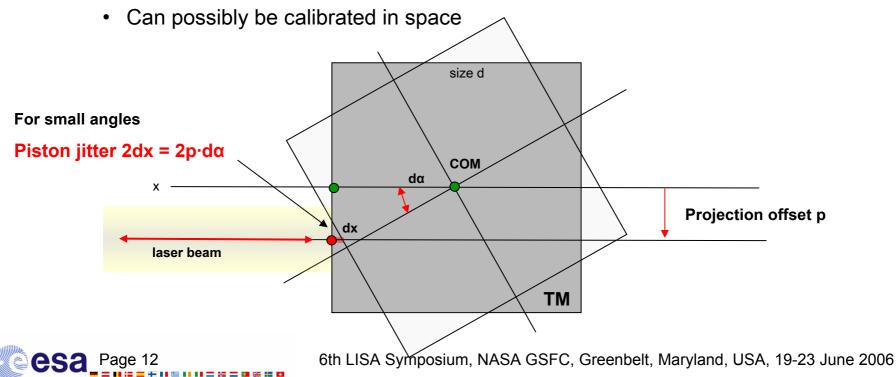
- Test mass attitude to piston jitter crosstalk caused by lateral offset of inertial sensor optical readout beam effective line of sight with respect to the test mass centre (already in LISA Pathfinder).
- Transmitter beam line of sight jitter (due to local spacecraft attitude jitter) crosstalk caused by lateral offset of the outer space line of sight projected backwards- with respect to the test mass centre.
- Received beam line of sight jitter (due to local spacecraft attitude jitter)
 crosstalk caused by lateral offset of the outer space line of sight -projected
 backwards- with respect to the test mass centre.
- Received beam phase jitter, caused by remote transmitting spacecraft pointing jitter and a mismatch of jitter centre and laser phase centre.
- Optical path length changes encountered by the beam while repointing or jittering and caused by optical imperfections (substrate inhomogenity, optical surface aberrations "phase walk", actuated mirror pointing jitter and piston bias, tolerances in pupil planes locations)



Test mass pointing/phase jitter cross-coupling effects



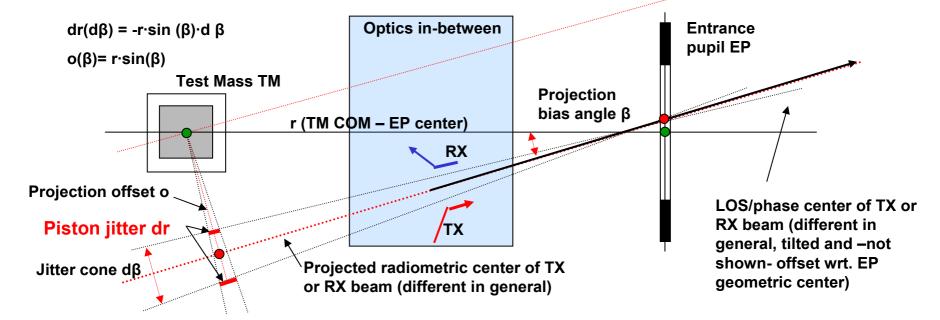
- Test mass (as active mirror) geometric projection effects p=5 μm and 10 nrad cause piston 1 pm; jitter dp= 1 nm negligible
- For backside IFO or ORO also manufacturing tolerances (ortogonality, parallelism of TM surface planes): ca 10 µrad tilt (2") require 100 nm lateral stability
- Tilt projection of laser after reflection: negligible (cos-effect)



Local optics pointing/phase jitter crosscoupling effects



- Imperfect location of pupil planes in optics causes angular to piston coupling between entrance pupil and detector
- An offset of effective inter-S/C line of sight (phase center axis) for both, TX and RX beam projection with respect to TM COM (the effective phase measurement reference point) intersection causes severe pointing/phase jitter cross-coupling (offset 4 mm causes 40 pm piston at 10 nrad/√Hz jitter)

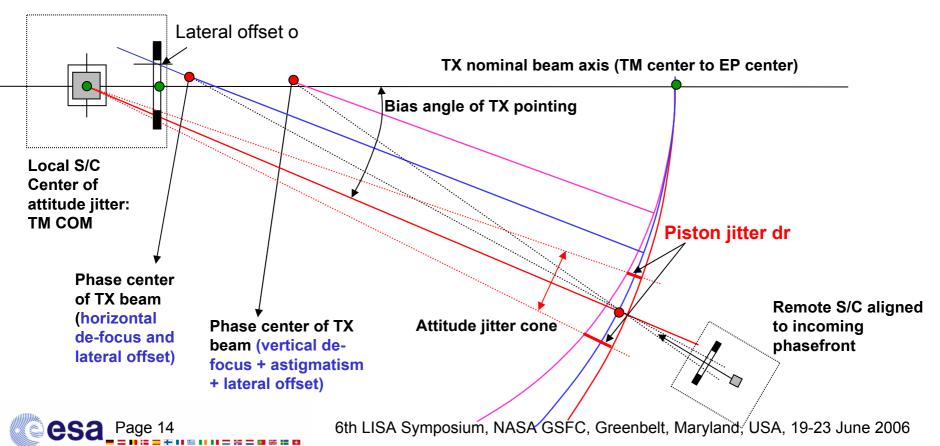




Remote (far field) pointing/phase jitter crosscoupling effects "Flat spot"



- Caused by optics aberrations, in particular: de-focus and astigmatism ($< \lambda/40$ ok)
- Radial offset of TX beam phase center and attitude jitter center (re-focus)
- Differential phase center radii (astigmatism)
- Optical asymmetries and lateral offset of radiometric TX beam axis in exit pupil



Geometric pointing/phase crosstalk effects (2)



- Cross talk from pointing jitter to laser phase jitter cannot be avoided within achievable alignment and radiometric calibration tolerances, combined with feasible attitude control authority (typ. 10 nrad/√Hz in outer space).
- Astrium proposes to utilise the very accurate and sufficient instantaneous pointing knowledge provided by the differential wavefront sensing of the heterodyne phase meters (200 prad expected) to correct the phase signal accordingly after in orbit calibration of the crosstalk function. That approach has significant impact on system and optics design.
- The pointing reference is the incoming wavefront plane at the location of the entrance pupil but sensed by the heterodyne science detector. Hence, any "weak" pointing transfer en route degrades the pointing (jitter) knowledge. Challenging pointing jitter requirements result for actuators in the path (point ahead, breathing angle compensator).
- These cross talk effects are always present, independently of a particular payload configuration and optics realisation. They are simply a result of the system geometry and dynamics.
- Their mitigation has a strong impact on the optical system configuration and technical realisation, and is specific for the various architectures under consideration.





2.LISA payload architecture: Present baseline

LISA payload configuration in sciencecraft Present baseline



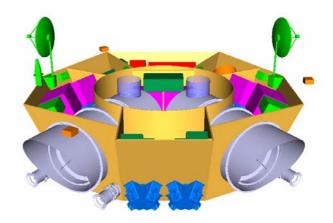
- Two separate optical assemblies each comprising telescope, optical bench and inertial sensor
- Both assemblies articulated as a whole to compensate annual angular "breathing"
- Inter-spacecraft and intra-spacecraft interferometry separated (strap down)

Advantages:

- Optics path in optical assembly (almost!) stationary -> reduced phase walk
- Two adjacent interferometer arms (almost!) functionally separated -> inherent redundancy
- LTP/LPF heritage for intra-spacecraft interferometry

Disavantages:

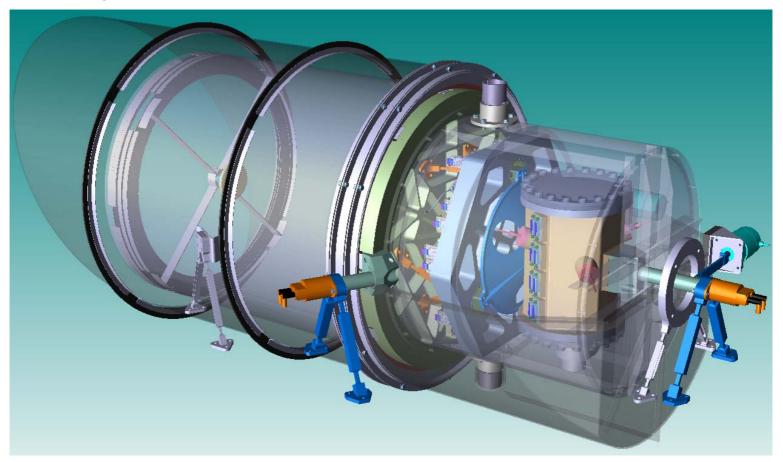
- Large, volume and mass driving configuration
- Flexible laser link between two assemblies required
- Complexity and costs (TBC)





Current design status of one LISA optical assembly







System overview in Peter Gath's talk on Friday

Optical assembly configuration in Dennis Weise's poster



New features in the present study payload baseline



New payload features proposed and introduced in the study (as compared to Feasibility Study FTR, 2000) include:

- Two-step interferometry (strap-down architecture) decoupling technically and functionally inertial sensor optical readout (ORO) and inter-spacecraft interferometry.
- On-bench dedicated variable point ahead actuator mechanism.
- Frequency swap for both, ORO and inter-spacecraft interferometer (using same laser sources).
- Optical bench oriented perpendicular to telescope line of sight.
- Open vacuum system throughout with venting into space (option only).
- Constraints from local geometric pointing/phase crosstalk effects accounted for.
- Defined pupil plane locations in optical chain
- Opto-mechanical configuration optimized for actuation accommodation, launch loads and thermo-elastic stability.





3.LISA alternative payload architecture: Single inertial sensor/ in-field pointing

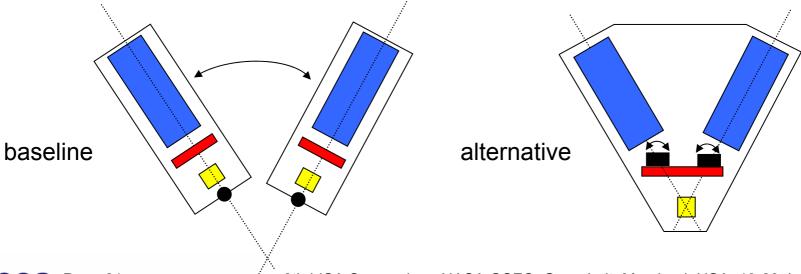


An alternative payload configuration



A promising novel concept is characterized from optics point of view by:

- A single optical bench and active inertial sensor, serving both adjacent interferometer arms.
- Two rigidly connected telescopes.
- The "breathing angle" compensation is accomplished by in-field of view pointing actuation of the lasers line of sight.
- Telescopes off-axis (straylight)



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An alternative payload configuration



Single inertial sensor concepts are an obvious choice in an attempt to simplify the LISA payload:

- A big advantage would be that no sophisticated electrostatic suspension and capacitive readout is required.
- For a <u>cubic test mass</u>, only a presumably simple attitude suspension is necessary;
- For a spherical test mass no suspension at all is necessary. The spacecraft simply follows the test mass in free fall guided by a sensitive optical readout of the relative position to the optical bench and in attitude by the incoming wavefronts from the adjacent spacecrafts.



However, intriguing at first sight, these concepts have their specific problem areas.

Only concepts featuring a combination of suitable line of sight articulation and single optical bench/inertial sensor are of particular interest.

Also the redundancy implementation at various system levels is not as obvious as in the present baseline.



Single test mass/in-field-of-view pointing architecture



2005

design

Advantages

- High potential for significant savings in mass, volume, complexity and costs (TBC)
- Exploits best advantages from strap-down concept
- No suspension loops for positional Degrees of Freedom required (only "simple" TM attitude actuation for cubic test mass)
- Single optical bench for inter-spacecraft interferometry and inertial sensor optical metrology (no "backside" interferometry necessary)

 Single on-bench in-field-of view actuator replaces complex actuation of two large assemblies, but needs attitude sensor (interferometer or optical truss)

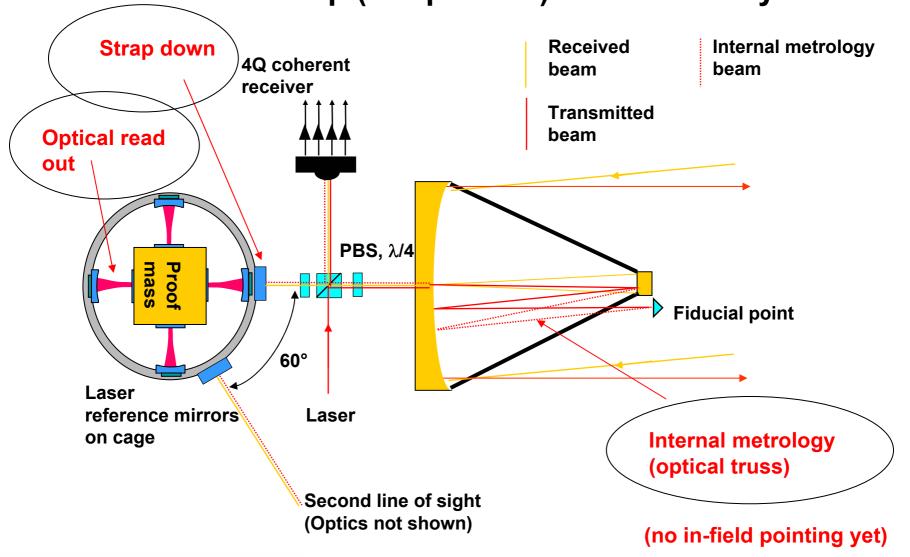
Disadvantages

- Novel concept proposed by Astrium without heritage
- Not analysed in detail yet
- Redundancy implementation not straightforward (inertial sensor)
- Breathing angle projection effects more significant
- Optical piston walk while changing line of sight inside FOV (to be calibrated or monitored)

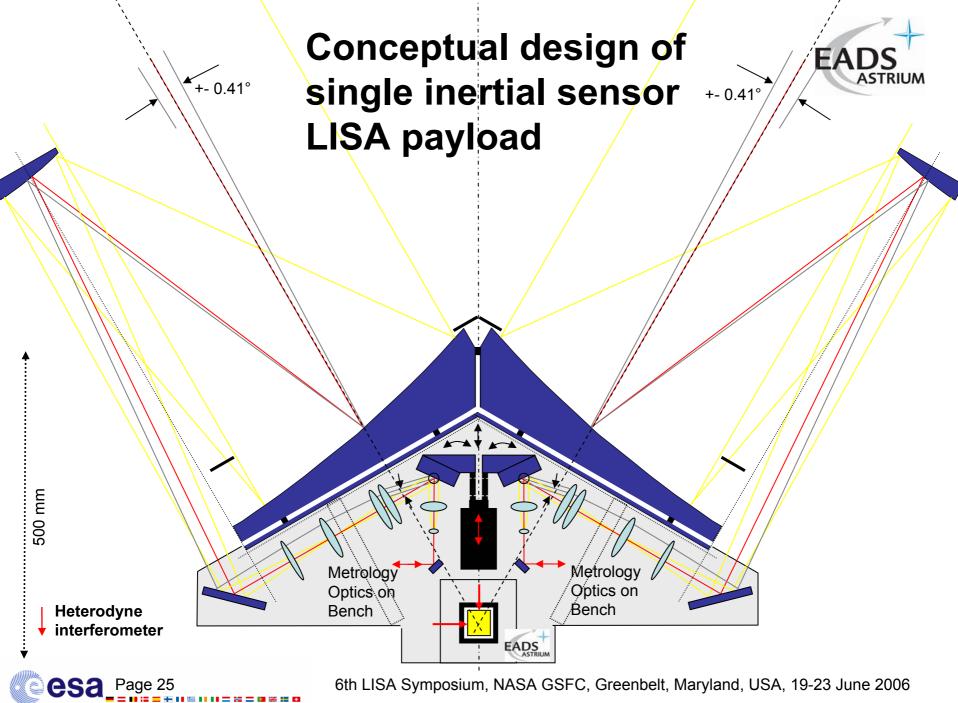


Feasibility study early (1999) concepts of optical EADS read out and 2 step (strap-down) interferometry









Design considerations for single inertial sensor LISA payload architecture



- Structural configuration (material, CTE, stiffness E)
- The single active optical read out inertial sensor
 - Cubic versus spherical test mass
 - Optical and capacitive read out needs (which DOF, resolution, range)
 - Absolute versus relative read out needs (spherical truss stabilises absolute position)
 - Actuation needs (electrostatic, mechanical, none)
- The in-field beam pointing telescope
 - Optics (lenses/transmissive, mirrors/all-reflective)
 - Actuation jitter and phase walk
 - Internal metrology and phase walk calibration
 - Symmetric versus off-axis telescope
- Optical bench functions, auxiliary interferometer sensing
- Reliability and Redundancy at all engineering levels



Design considerations The in-field beam pointing telescope:



Requirements:

- Entrance pupil close to test mass center to minimize local projection effects (lever arm). M1 plane good (ca. 350 mm; ok!).
- Imaged pupil planes in strategic locations with sufficient space, in particular in in-field pointing actuator, differential (point ahead) actuator, detector planes
- Requirements on actuator depending on optical magnifications (V e.g. 100 for point ahead, 10 to 20 for in-field pointing locations, resp.)
- Typically in MBW: 1 nrad/√Hz jitter; piston few pm
- All-reflective optics preferred in order to minimize path length changes in transmissive optics due to thermal fluctuations/inhomogenities and straylight from narcissus reflections.
- Transmissive optics with integral bulk optical path ca. 100 mm still ok; preferred for more compact design
- Off-axis design preferred to avoid straylight from M2 spider and to ease actuator accommodation

Candidate options:

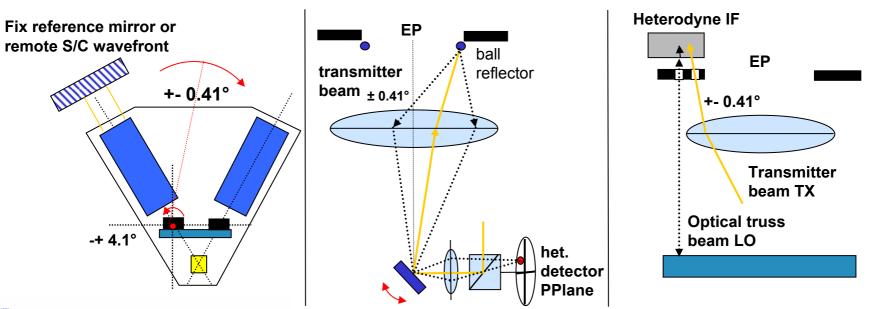
- TMA Korsch Schiefspiegler all reflective or incl. field lens assembly
- Cassegrain, dito



Optical metrology and calibration options:

How to calibrate or monitor at pm accuracy within the LISA measurement band (!) a piston/phase walk during re-pointing ??

- Passive system and on-ground and in-orbit phase walk calibration runs
- Internal optical truss using existing science heterodyne 4Q-detector
- Internal optical truss requiring additional phase meters (6)
- Dedicated actuator sensor and calibration
- Further references: SIM pm metrology, POINTS (holo-grating on M1)



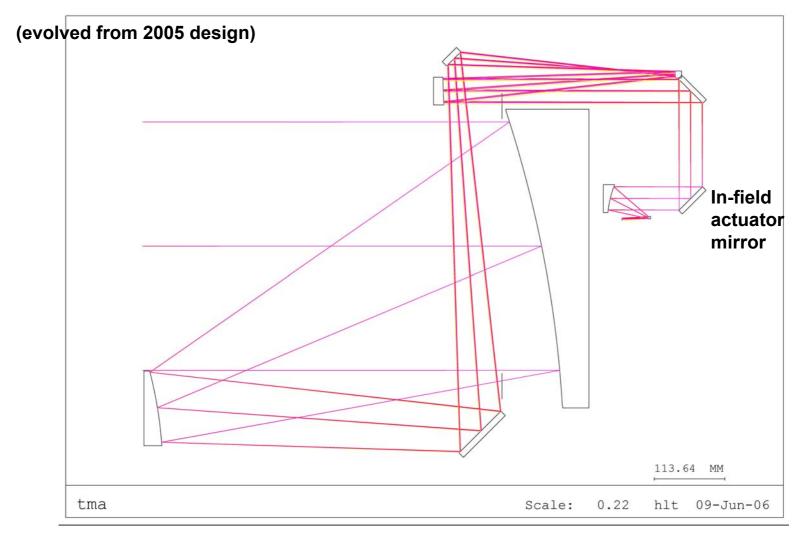


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EAD

Preliminary optical design of all reflective infield beam pointing telescope:

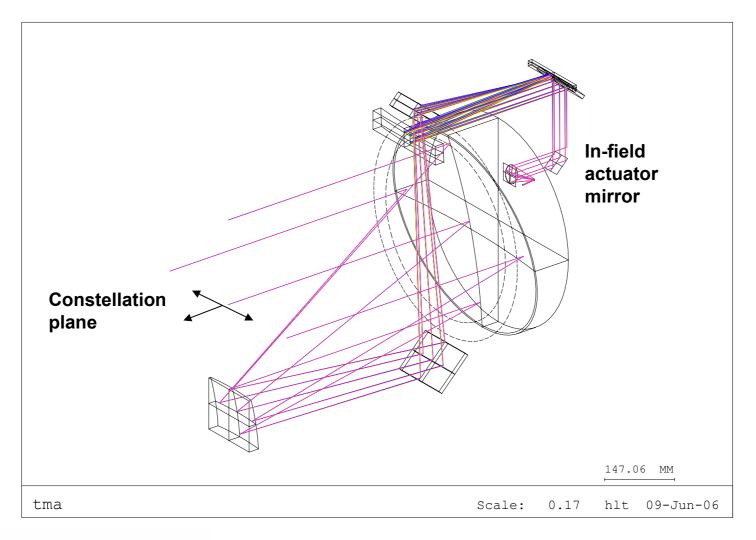






Preliminary optical design of all reflective infield beam pointing telescope:

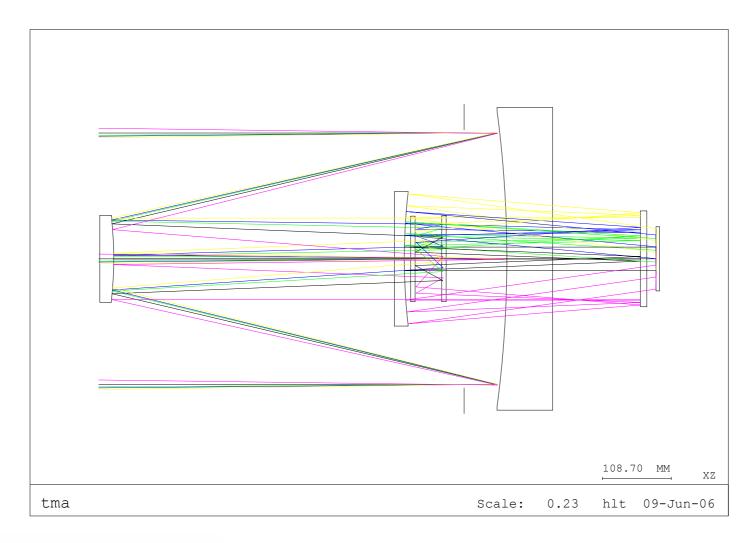






Preliminary optical design of all reflective infield beam pointing telescope:







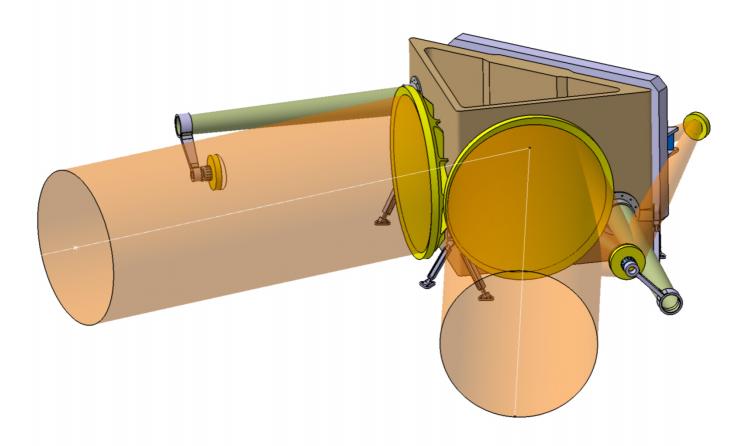
Preliminary optical design of all reflective infield beam pointing telescope: Back optics folded behind M1 (conceptual only)





Preliminary layout of alternative configuration (2005 off-axis telescope design)





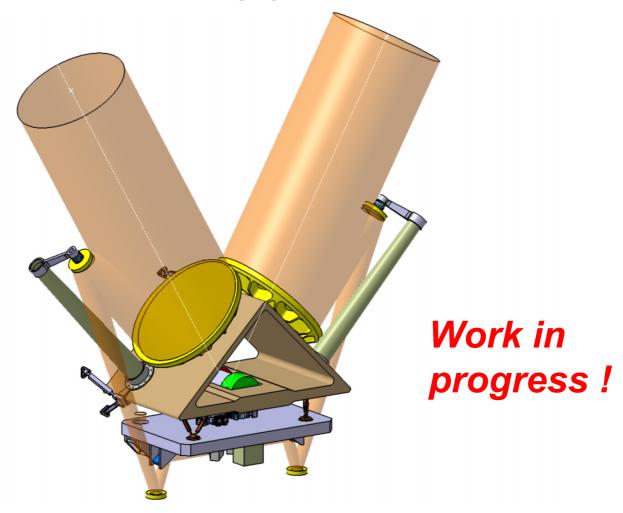


Preliminary layout of alternative configuration (2005 off-axis telescope design) EADS ASTRIU



Preliminary layout of alternative configuration (2005 off-axis telescope design)





Preliminary Mass Budget



Item	New Mass (kg)	Current Mass (kg)
Structural Parts and Harness	123.1	157.5
Electronic Boxes	81.0	101.2
Total Payload	204.1	258.7
30% Margin	61.2	77.6
Total Payload with Margin	265.3	336.3

- Current baseline launch wet mass is approx. 4643.1 (requires Atlas 531 launcher)
- Reduction by 1 kg on S/C or payload side yields approx. 5.7 kg reduction on the launch stack (due to 30% margin philosophy and required propellant)
 - → launch mass reduced by approx. 405 kg
 - → comfortably fits on Delta 4450 or Atlas 521 (cost reduction w.r.t. Atlas 531)
- Reduced number of boxes and reduced power consumption can yield a smaller solar panel diameter
 - → additional mass savings in S/C structural mass and propulsion module structural mass





4.Single spherical test mass as an option?

Design Considerations: The single spherical optical read out inertial sensor



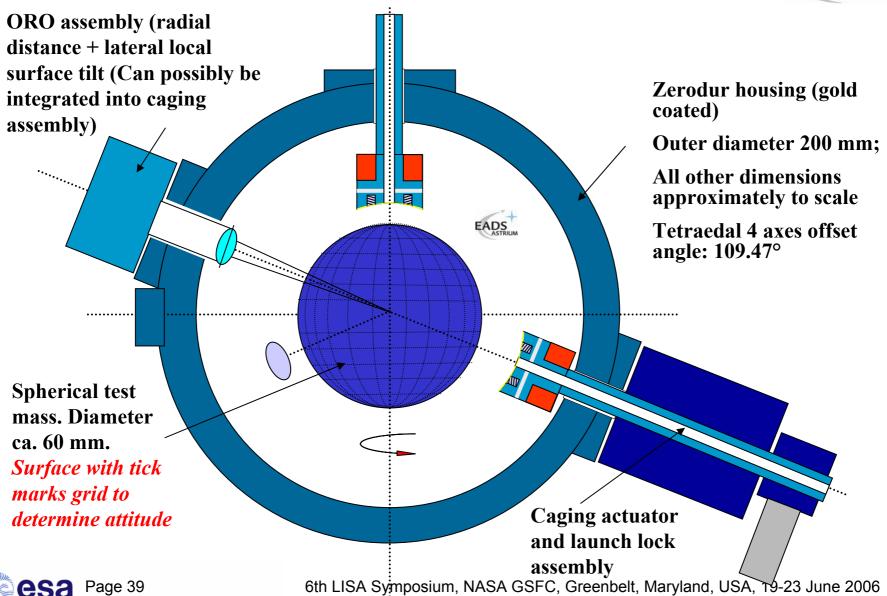
Preliminalry conceptual features:

- Tetraedal arrangement of precision caging, release and re-caging mechanism
- Eddy current or piezo/mechanical spin up/down
- Tetraedal arrangement of optical readout for relative distance and local beam steering measurement (4Q differential wavefront sensing; 16 signals)
- Arrangement allows absolute positioning, monitoring, repositioning (ground alignment in operational position)
- Kept in relative position by drag free control of spacecraft
- Calibration of "un-roundness" of sphere in fast spin mode
- Sphere operated in slow spin and allowed to tumble
- Attitude monitored from data reduction and "grid marks" applied to sphere (circles, grating?) while passing laser spots
- No electrical fields inside housing (but optionally possible)



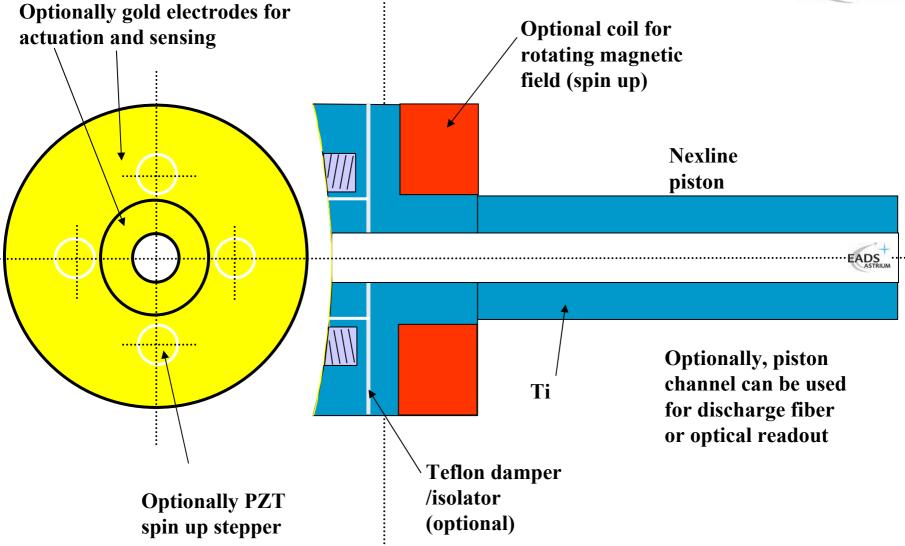
Tetraedal spherical test mass assembly





Caging, release and sensing actuator piston

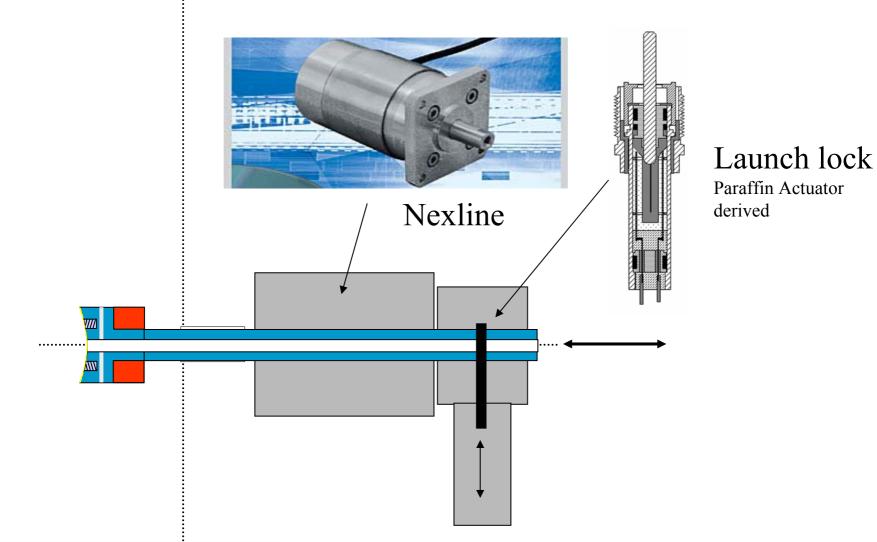






Caging, release and sensing actuator piston

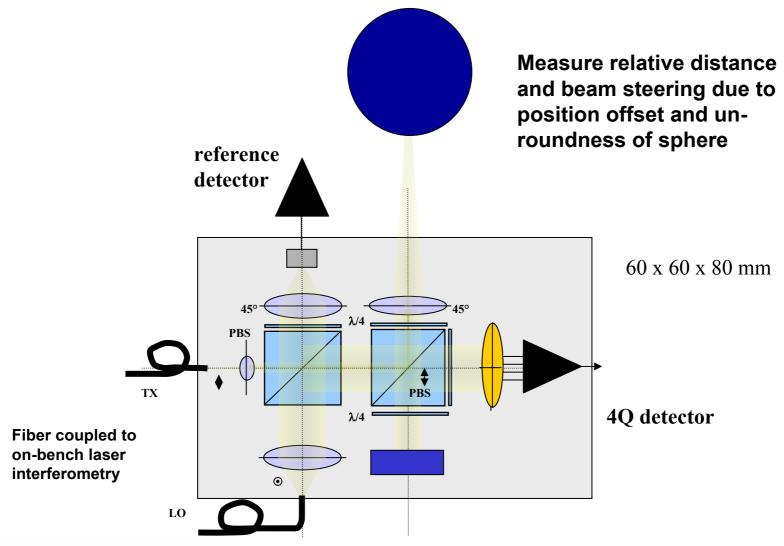






Optical readout unit concept: Polarisation heterodyne interferometer

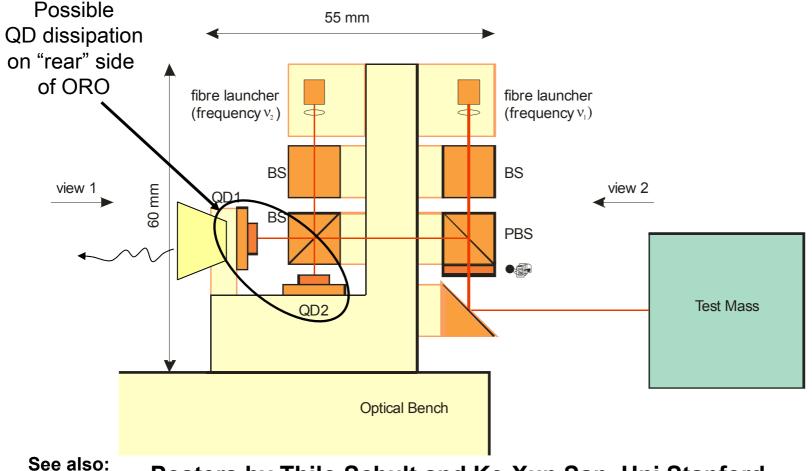






Humbolt University / EADS Astrium optical readout concept (breadboard ready)





Posters by Thilo Schult and Ke-Xun San, Uni Stanford Presentation by Cliff Speake, Uni Birmingham



Summary



- Alternative LISA payload configuration identified and assessed on conceptual level
- Key ingredients are: single inertial sensor, in-field laser beam pointing, strap down and optical read out
- Feasibility depends critically on calibration or monitoring of inband optical piston/phase walk and received beam path pointing jitter while re-pointing
- Architecture fits well to cubic and spherical test mass option
- Conceptual layout of spherical test mass inertial sensor still to be verified
- High potential for volume, mass and cost saving still to be verified
- Good heritage from LISA Pathfinder (except spherical test mass option)
- Not mature enough for fair benchmarking with present baseline, but work in progress

